TECHNICAL REPORT

Contract N8onr-66904

AMHERST COLLEGE OBSERVATORY

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Abstract

In section 1 of the following report is a description of the mechanical details of the Amherst College photoelectric photometer. In section 2 is a description of the measuring system which permits determining photocurrents either with a zero offset method or with the conventional measurement of voltage drop across a large input resistor. Section 3 includes a discussion of the design details of various power supplies and associated electronic apparatus. In section 4 is a discussion of the design of the D.C. amplifier used in the measuring system.

The general characteristics of the D.C. amplifier are as follows:

1. Grid current --- 10^{-13} amperes.
2. Input resistance --- adjustable in eleven steps from 0 to 1600 megohms.
3. Voltage gain --- 0.783.
4. Output impedance --- 15.3 ohms for a load resistance of 100 ohms.
5. Linearity --- better than 0.1%.
6. Drift (after warm-up) --- 0.1 millivolt per hour.

I. Mechanical Details of Photometer

This report describes the photoelectric photometer constructed at Amherst College Observatory under contract N8onr - 66904. The photometer was designed and constructed to be used with the 18-inch Clark refractor at Amherst College. The telescope itself is a visual refractor with a focal length of 277 inches operating at f/15.4.

Figure 1 is a photograph of the photometer proper. The photometer has the following sub-assemblies: a brass pipe, machined to fit the end of the telescope, which slides in and out along the telescope axis in order to effect focussing. This brass tube carries an engraved scale on it to permit resetting a given focus. Its position is controlled by a rack and pinion. The main body of the photometer is captured on the brass pipe by a flange and retaining ring. The photometer may be rotated with respect to the pipe permitting setting the eye-piece in any convenient orientation. A box carrying color filters may be slid transversoly through the photometer housing and stopped with any one of three color filters located in the converging cone of light. A spring-loaded ball and detent mechanism indicates when the location of a given color filter is proper.

The arrangements for guiding and finding are indicated in figure 2. A relatively large, optically flat front surface mirror may deflect the converging cone of light to a focus in front of a low-power eye-piece. This eye-piece gives a fairly large field of view and utilizes the whole aperture of the telescope, thereby facilitating the selection of the given star desired. Once the desired star has been found, the telescope is moved to bring the star to the center of the field of view. The diagonal mirror is then slid back out of the converging cone of light. The light continues through any color filter that may be in position on to a smaller diagonal mirror at the lower end of the optical column. This diagonal mirror deflects the converging cone of light to a focus in front of lens A, set in a small brass tube. This lens receives the rays diverging from a focus and collimates them. The rays continue through a thin unsilvered microscope cover glass, through a second lens and thence to a focus in front of a high power guiding eye-piece. A short distance above the diagonal surface of the microscope cover glass is a reticle, consisting of a circular disk of glass coated with a metal film in which has been engraved a very small circle. Light from a "Grain of Wheat" lamp above the reticle passes through this engraved circle. The reticle is at the focus of lens C. The light from the reticle therefore is collimated by the lens and passes down through the diagonal microscope cover glass. A portion of the light reflects from the cover glass, passing through lens B to a common focus with the light from the star. When the telescope is set properly the star appears as nearly a point of light at the center of a bright circle. The position of the reticle in the focal plane of lens C may be adjusted by controlling screws. Once the telescope has been oriented properly the second diagonal mirror is removed and the light continues to a focus.

At the lower end of the optical column is a movable slide carrying a number of small diaphragms of various sizes. Any one of these diaphragms may be set on the axis of the photometer with the aid of a spring-loaded plunger and detent mechanism. If the telescope and photometer have been adjusted properly the star image will appear in focus at the center of the selected diaphragm. The longitudinal position of the photometer is determined by finding the focus of the telescope with the aid of a knife edge test. The reading on the engraved scale on the brass pipe is then read and recorded. This setting naturally will vary with different color filters. The adjusting screws controlling the position of the reticle above lens C are adjusted so that when the star image appears in the center of the ring of light from the reticle, the star image will also appear at the center of the focal plane diaphragm when the diagonal mirror is slid out of the converging cone of light. The function of the diaphragm is to remove background light from the sky permitting only the light from the selected star to pass through to the phototube along with a very small amount of background sky illumination. The light which passes through the diaphragm goes through a field lens and thence to the sensitive surface of the phototube. The function of the field lens is to image the telescope objective on the photocathode. This arrangement prevents motion of the image on the photocathode even though the image in the focal plane of the telescope may move about slightly due to atmospheric tremor.

Figure 3 is a photograph of the housing containing the phototube and subminiature amplifier. This housing is a double-walled container so arranged that the phototube may be refrigerated with dry ice. The space between the inner and outer walls of the container is filled with Santocel insulation. The dry ice supply need be replenished only once during the course of a night's observing. The light entering the phototube housing passes through a small piece of cellophane. This material does not fog easily even at dry ice temperatures and it has not been necessary to provide any heating coil to prevent fogging of the entrance window. Figure 4 is a photograph of the subminiature amplifier which fits into the phototube housing. The signal lead passing from the phototube anode to the amplifier input goes through the inner wall of the phototube housing, through the Santocel insulation and then through an insulated header in a brass plate at the bottom of the amplifier well. Depending on the sensitivity setting of the amplifier the resistance from this lead to ground may be as great as one thousand megohms. The current carried by the lead will rarely be as great as one microampere. The arrangement of having the signal lead entirely enclosed inside the phototube housing has the great advantage of avoiding leakage troubles due to atmospheric moisture. Leakage troubles have been fairly serious at some observatories because the photometer must operate at temperature and humidity conditions which are the same as those outside the observatory building. The domes which contain telescopes may never be heated because of the disastrous effects such heating would have on the steadiness of the star image produced in the telescope.

II. Measuring System

In figure 5 is a block diagram of the measuring system. The dark slide is actually the tube carrying the second diagonal mirror in the photometer optical column. This dark slide operates two microswitches. One microswitch turns on the "Grain of Wheat" lamp for guiding purposes when the dark slide is pushed in. The second microswitch is the one indicated in the block diagram and operates when the dark slide is retracted. On withdrawing the dark slide light falls on the phototube and produces a photocurrent which, flowing through resistor R, produces a signal voltage. In series with this voltage is the internal voltage of the switch-in potentiometer. The polarity is such that the voltage produced across resistor R is opposed by the internal voltage of the potentiometer. The D.C. amplifier consequently sees as an input signal the difference between these two voltages. With no light falling on the phototube the microswitch actuated by the dark slide connects the resistor R directly across the input to the D.C. amplifier. It is possible to set the switch-in potentiometer voltage to zero and in this location the entire measuring circuit behaves in a manner similar to the ordinary photoelectric photometer. With a voltage set in the switch-in potentiometer the behavior of the measuring circuit is modified in the following manner. With the dark slide in position so that no light falls on the phototube the D.C. amplifier has an input signal which depends upon the dark current of the phototube. The zero control of the D.C. amplifier permits adjusting the position of the Brown recorder pen at perhaps 10% of full scale deflection. On retracting the dark slide the light falling on the phototube produces a signal voltage across the resistor R; however the microswitch connected to the dark slide simultaneously trnasfers the lower input terminal of the D.C. amplifier from one side of the switch-in potentiometer to the other side in such a way that the new input voltage seen by the D.C. amplifier is the difference between the new voltage across resistor R and the voltage previously set in the switch-in potentiometer. If this voltage in the switch-in potentiometer is exactly equal to the product of the change in current through resistor R and its resistance, the pen of the Brown recorder remains in its original position. The action of the microswitch and switch-in potentiometer therefore is essentially a means of displacing the zero of the recorder by a known amount at the same time that the light falling on the phototube produces a signal at the input of the D.C. amplifier. The Brown recorder has a sensitivity such that ten millivolts input signal produces full scale deflection. The switch-in potentiometer has two decades, one decade giving steps of one millivolt and the other decade giving steps of ten millivolts. Ideally the D.C. amplifier should have a voltage gain of exactly one. If this is so, each successive step of the first switch-in potentiometer decade displaces the recorder zero by ten percent of full scale while each step of the second decade displaces the recorder zero by one full scale width. The advantage of this arrangement is the following: in photometry of stars the precision ideally should be limited by the stellar scintillation produced by fluctuations in transmission through the earth's atmosphere. However on some exceptionally good nights the error in a given observation is determined more by the width of the recorder pen line than by the atmospheric scintillations. With the type of observations described above it is possible to set the sensitivity of the D.C. amplifier such that without the switch-in potentiometer the signal produced would give much greater than full scale deflection on the Brown recorder. The presence of the switch-in potentiometer displaces the recorder zero by a known amount so that the top end of the pen line remains on scale. This permits amplification of the atmospheric scintillation effects relative to the width of the pen line by a factor of approximately ten. Figure 6 gives a general view of the chassis containing the switch-in potentiometer, the regulating circuit for the photomultiplier tube and the power supplies for these circuits.

III. Design of Regulators, Potentiometer, and HV Supply

The usual degenerative regulator has a circuit arrangement as shown in figure 7. By use of the customary relationship $i_p r_p = e_{pk} + \mu e_{gk}$ it is possible to calculate the degree of ripple reduction achieved by a given regulator. Referring to the labels on figure 7 the following relationships follow immediately.

$$i_p = \frac{E_o + e_R'}{Z_L}$$

where Z_L = the parallel combination of Z_L', R_s and the internal impedance of the amplifier (-G)

$$E_o + e_R' = \frac{e_R Z_L + E_{bb} Z_L - \mu G Z_L E_c}{r_p + Z_L + \mu Z_L (1 + \alpha G)}$$

where $E_c = \frac{\bar{e}_g - \alpha E_o}{1 - G}$
(assuming $e_g = \bar{e}_g + \tilde{e}_g$)

hence, $$\frac{e_R'}{e_R} = \frac{1}{\frac{r_p}{Z_L} + 1 + \mu (1 + \alpha G)}$$

The above relationships assume that there is zero phase shift throughout the entire regulator. In order to provide a high degree of regulation the feed back amplifier with gain indicated as -G should have a large gain and at the same time a wide band width. It will be observed from the above relationship that the larger the value for G the better the degree of regulation. However a degree of diminishing returns is rapidly reached since in order to provide small phase shift the amplifier must have a very wide band width and if at the same time the gain of the feed back amplifier is very large then the amplifier itself introduces appreciable noise into the output. The B supply for the switch-in potentiometer and phototube regulator amplifiers is of this variety. Its circuit diagram appears in figure 8.

The quality of this regulator need not be extremely high, regulating accuracy of 0.1 being entirely adequate. This power supply uses a battery standard which has been found quite satisfactory. No current is drawn from the battery and so it will last for its full shelf life as an operating component of the regulator. A check of the degree of regulation of the 260 volt supply was made by connecting together a number of batteries in series to provide a standard 260 volt supply and observing the difference between this supply and the electronic supply on the differential input of a Tektronix oscilloscope. The 260 volt electronic supply operated with its normal load applied. The input impedance of the Tektronix oscilloscope is large enough that a negligible current was drawn from the battery standard. A ripple with an amplitude of .015 volts was observed in the output, being mainly 60 cycles. A considerable portion of this came from the rather long leads extending from the oscilloscope to the regulator and battery standard. The random low frequency drift was less than .001 volts and during an observing period of five minutes there was a gradual drift amounting to .008 volts. It is apparent that the degree of stability is better than 0.1%. Assuming that the drift for a five minute period would extend by an equal amount and in the same direction for a period of one hour, this would give an over-all drift of less than .05 % per hour. The transconductance and amplification factors of the various tubes in the feed back amplifier were determined on a vacuum tube bridge. The calculated value for $\frac{e_R'}{e_R}$ was 1/300,000. It is conceivable that a still higher degree of regulation could be achieved by operating the heaters of the feed back amplifier on regulated D.C. It is necessary to make a fairly careful choice of the circuit values for the 12AU7 stage feeding the 47 regulator tubes to avoid instability in the regulator. It will be observed that the plate currents in successive stages of the regulator become successively larger and impedances in successive stages become successively lower. Attempts to use too large load resistors in the final stages of the regulator amplifier, particularly the resistor in series with the control grids of the series control tubes, frequently produce difficulties because of appreciable grid current drawn by the series control tubes. At the same time phase shifts produced by large input capacitance for the control tubes can cause low apparent regulation factors. Wire wound resistors in the first stage of the control amplifier insure stability of components with temperature. The gain of the first stage is sufficient that the components in successive stages need not have the extreme performance available for wire wound resistors.

Figure 10 is a circuit diagram of the switch-in potentiometer. There are two supplies for the regulating amplifier of the switch-in potentiometer. One of these is the regulated +260 volt supply described above. The other is a -150 volt regulated supply provided by a VR tube. The function of the potentiometer has been described above. If it is to perform its function properly the voltage available across the two decades of the potentiometer must maintain accurate calibration. Moreover if the potentiometer is to be used to displace the zero of the Brown recorder by as much as ten chart widths and if the recorder is to be read to an accuracy of 0.1% then it is apparent that the calibration of the switch-in potentiometer voltages must be accurate to 0.01% to avoid introducing systematic errors. This accuracy is accomplished by using two control loops. With the potentiometer switches set at the middle of their ranges and with the grid of the 6J7 at approximately -1.65 volts then the current flowing through the 6J7 is very nearly one milliampere. The voltage at the cathode of the 6J7 is sampled by a resistive divider network consisting of a 5 megohm and a 1 megohm resistor. The sample voltage is fed to one grid of a 12AX7 duotriode. With the Stevens-Arnold chopper disconnected from the circuit the grid voltage of the other half of the 12AX7 is maintained at +1.[illegible]2 volts. This voltage balances the sample voltage. The first 12AX7 acts as a differential amplifier and the output signal feeds a second 12AX7 which in turn controls the grid of the 6J7, completing the control loop. In operation the setup procedure for the potentiometer is as follows: after turning on the power supply approximately twenty minutes is allowed for warm-up time, then the two ganged potentiometers dividing the output of the first 12AX7 are set so that the voltage level at the grids of the second 12AX7 produce the proper bias voltage on the 6J7. The one microfarad capacitor bypassing the 6 megohm resistor in the sampling network gives this network a long time constant and consequently a certain amount of time is required to permit the 6J7 to establish its final operating voltage. When the current flowing through the switch-in potentiometer is properly set, the voltage appearing across the 1018.8 ohm precision resistor connecting from ground to the lower terminal of the decades equals a standard cell voltage. A thermostated standard cell is connected so that its EMF subtracts from the voltage appearing across this precision resistor. With the proper current flowing, the difference is zero. If the regulator on-off switch is now closed any error voltage will appear as a D.C. voltage at the input of the Stevens-Arnold chopper. This chopper converts the error voltage to a 60 cycle square wave which feeds to the input grid of a 6AU6. There are two successive stages of amplification and a cathode follower output. The A.C. amplifier has a fairly wide band width to permit faithful reproduction of the 60 cycle square wave with little phase shift. The cathode follower has a low output impedance which will provide a short charging time constant for the capacitor at the output of the demodulating chopper. There is a potentiometer in the cathode of the cathode follower which permits setting the cathode voltage, after adequate warm-up time, to ground potential. This is a necessary feature since if the cathode is at a positive potential with respect to ground there will be a D.C. voltage developed across the 1/10th microfarad capacitor since it, along with the .22 microfarad capacitor, will act as a capacity voltage divider at those instants that the vibrating reed connects the two capacitors together. It is desired to have zero output voltage for zero error voltage at the input of the chopper, hence the necessity for setting the D.C. output level of the cathode follower to ground potential. The A.C. amplifier has a total gain of approximately 500 and is exceedingly linear over wide signal ranges. The demodulated output after passing through a series filter, goes directly to an input grid of the 12AX7 regulator tube. This forms the second regulating loop and corrects for any minor error in the initial setting of the current through the 6J7. The procedure in summary is as follows: after a twenty minute warm-up time, the ganged potentiometers in the first 12AX7 D.C. amplifier stage are set so that the cathode voltage of the 6J7 is eleven volts positive with respect to ground. The potentiometer in the cathode of the 6AU6 cathode follower is set so that the cathode voltage is at ground potential. The regulator on-off switch connecting from the standard cell to the input of the Stevens-Arnold chopper is closed permitting the chopper and A.C. amplifier to take over control of the circuit. With the thermostatic control for the standard cell, the entire instrument may be operated at the ambient temperatures found in an observatory dome and has operated well down to -20 centigrade. The calibration is maintained independently of the setting of either decade switch. The stability of the switch-in potentiometer was checked by connecting an external standard cell in such a direction as to subtract from the voltage produced across the 1018.8 ohm resistor and measuring the difference on a Brown recording potentiometer. Full-scale deflection on the Brown recorder corresponds to an input voltage of 10 millivolts. Consequently voltage variations of 1% in the output would produce full-scale deflection, while 1 chart unit on the Brown recorder corresponds to an output variation of 0.01%. Without the chopper amplifier operating but after an adequate warm-up time, there were erratic output drifts amounting to 0.1%. Closing the regulate switch to the chopper amplifier reduced those erratic drifts by a factor of at least 10. There were residual erratic drifts, however, which occasionally became as large as 0.02 %. These were superposed on a slow average drift which was taken to represent a gradual temperature change in the standard cell voltage. The output drift is somewhat larger than was originally expected and probably arises from the D.C. amplifier between the chopper amplifier and the 6J7 control tube. In view of the excellent regulation of the +260 volt supply it would probably be possible to eliminate this D.C. amplifier altogether. It is also quite possible that the VR tube contributes appreciably to the instability of the output. It would undoubtedly be better to use a double capacitor coupling for the output to the demodulating contacts, bringing the common junction of the two output capacitors to ground via a series resistor. This arrangement would assure the elimination of any capacitive voltage divider effects. It is found in practice that the D.C. voltage level at the cathode of the cathode follower does vary appreciable, over perhaps a volt in a period of several hours.

The regulator for the photomultiplier supply is similar in most respects to the regulating amplifier for the switch-in potentiometer. With a few minor circuit changes the A.C. amplifier and the D.C. amplifier in this regulator are similar to those in the switch-in potentiometer. The photomultiplier supply, as is shown in figure 11, uses a 6SL7 suotriode as the control tube for the resistive bleeder supplying the various dynodes of the photomultiplier. The +260 volt and -150 volt regulated supplies for the regulating amplifier are the same as those for the switch-in potentiometer amplifier. The current to be regulated in this case is 1/10 milliampere while for the switch-in potentiometer the current to be regulated was 1 milliampere. The voltage levels for the photomultiplier supply are, generally speaking, considerably higher than for the switch-in potentiometer. These two facts have necessitated certain circuit modifications. The first regulating loop utilizing the two 12AX7's has a fairly high impedance sampling circuit. The circuit consists of a 100 megohm and a 25 megohm high voltage resistor connected in series across the output of the high voltage supply. The sampling point is so selected that nominally its voltage to ground is zero. Switch number 1 on figure 11 initially connects the sample point directly to ground. This permits the two 2500 volt capacitors to charge to their proper voltage. If the sample point were connected directly to the 12AX7 grid, the circuit would behave like a current integrator which would tend to maintain the 6SL7 in a cut-off condition for a very long period of time.

The setup procedure for this circuit is as follows. After turning on the power switch there is a one-minute delay in applying high voltage provided by the Amperite thermal relay. This permits the 6SL7 cathode to come up to operating temperature and avoids applying a large plate voltage without the tube being in an operating condition. After a twenty minute warm-up period, during which time switch number 1 has maintained the sample point at ground potential, the ganged potentiometers dividing the output of the first 12AX7 are set so that the voltage at the cathode of the 6SL7 is one volt positive with respect to ground. The potentiometer in the cathode of the 6AU6 cathode follower is then set so that the voltage at the cathode follower cathode is zero volts with respect to ground and then switch number 1 is moved so that the sample point now connects to the grid of the 12AX7 regulator tube. The ganged potentiometers in the 12AX7 stage may now be re-adjusted slightly, if necessary, to return the cathode voltage of the 6SL7 to one volt positive with respect to ground, and then switch number 2 is closed, inserting the standard cell and chopper amplifier in the regulating circuit.

The bleeder network feeding the various dynodes is soldered directly to the base pins of the photomultiplier. In general the photomultiplier will be refrigerated with dry ice which effectively thermostats the bleeder resistors. Since the current drawn from the photomultiplier supply is very small, and since the voltage levels are fairly high, it is particularly important that the filter capacitors in the supply have very high insulation resistance.

IV. Design of D.C. Amplifier

Figure 12 is a diagram of the subminiature D.C. amplifier. The amplifier acts essentially as an impedance transformer. It is designed to have a low output impedance feeding a ladder attenuator which in turn feeds a Brown 0-10 millivolt recording potentiometer. In principle it would be better not to have an attenuator between the amplifier output and the Brown recorder, and the amplifier should have unity voltage gain, thereby maintaining the calibration of the switch-in potentiometer in proper relationship to the voltage sensitivity of the recorder. However, as will be indicated below, the sensitivity of the present amplifier is less than one, while the sensitivity switch at the input is too coarse to permit eliminating the attenuator as a fine sensitivity device. For astronomical observations it would be an advantage to have an attenuator which would give sensitivity steps corresponding to changes of 0.1 in the apparent magnitude of stars. For a ladder attenuator, this would correspond to a value for a of 1.0965. (see Terman, "Radio Engineers' Handbook", p.215). Until very recently the balancing mechanism for recorders has worked best for source impedances of, at the most, approximately 200 ohms. The resistance values which happened to be on hand permitted assembling an attenuator with a=1.047.

The output stage of the D.C. amplifier consists of a double bridge-balanced circuit. Looking momentarily at one side of the bridge-balanced amplifier (figure 13), and considering the load resistance for the moment as infinite (i.e., there is no load connected from the cathode of T_1 to T_3), it is possible to analyze the behavior of the circuit in the following terms.

$$i_{p_1} = \frac{E_{bb} + \mu_1 e_1}{r_{p_1} + r_{p_3} + R_K(2+\mu_1+\mu_3)}$$

$$e_{o_1} = \frac{E_{bb} + g_{m_1} e_1}{\frac{1}{r_{p_1}} + \frac{1 + g_{m_1} R_K}{r_{p_3} + (2 + g_{m_3} r_{p_3}) R_K}}$$

$$\frac{\partial e_{o_1}}{\partial e_1} = \frac{\mu}{1 + \frac{r_p + \mu R_K}{r_p + (2+\mu) R_K}} \quad \text{(assuming identical tubes)}$$

The actual circuit of course has a load resistance which is of the same order of magnitude as the cathode resistors. The behavior of such a circuit may be analyzed in the following manner, assuming all tubes to be identical, and assuming a resistor R_L connected from the plate of T_2 to the plate of T_4. (Note the amplifier actually has R_L above the cathode resistors, because of D.C. requirements. This changes the analysis slightly) (see figure 13A).

$$i_1 = \frac{R_L + 2[r_p + (\mu+1) R_K]}{2[R_L + r_p + (\mu+1) R_K]} \left\{ \frac{E_{bb} + \mu e_1}{r_p + (\mu+1) R_K} - \frac{E_{bb} + \frac{1}{2}(e_1 + e_2)\mu}{R_L + 2[r_p + (\mu+1) R_K]} \right\}$$

$$i_2 = \frac{R_L + 2[r_p + (\mu+1) R_K]}{2[R_L + r_p + (\mu+1) R_K]} \left\{ \frac{E_{bb} + \mu e_2}{r_p + (\mu+1) R_K} - \frac{E_{bb} + \frac{1}{2}(e_1 + e_2)\mu}{R_L + 2[r_p + (\mu+1) R_K]} \right\}$$

$$i_1 - i_2 = \frac{R_L + 2[r_p + (\mu+1) R_K]}{2[R_L + r_p + (\mu+1) R_K]} \left\{ \frac{\mu(e_1 - e_2)}{r_p + (\mu+1) R_K} \right\}$$

$$i_L = \frac{\frac{1}{2}(e_1 - e_2)\mu}{R_L + r_p + (\mu+1) R_K}$$

$$e_o = \frac{\frac{1}{2}(e_1 - e_2)\mu R_L}{R_L + r_p + (\mu+1) R_K} \quad \text{For push-pull input, } e_1 - e_2 = 2e_i;\ \frac{e_o}{e_i} = \frac{\mu R_L}{R_L + r_p + (\mu+1) R_K}$$

It will be observed that the expressions for i_1 and i_2 consist of two parts. One part involves a term arising directly from the application of a signal voltage to the grid of the tube in question. The other expression involves a term which gives a common mode contribution to the signal current. In obtaining the difference between the two currents, however, the common mode current cancels out. The expression for the gain for a push-pull input signal is identical with the expression for the gain of a single triode amplifier with a cathode degeneration resistor R_k. If the load resistor has a fairly small value as is true in this particular amplifier, then the output tubes should have fairly low plate resistance and fairly high g_m. For given values of r_p and R maximum gain may be obtained by making R_k as small as possible. With the low value of load resistance used in the present application, the problem is more one of choosing R_k for good operating conditions of the tubes. The value of R in this application is of the order of magnitude of 100 ohms. Assuming a value for μ of 20 for the 6BF7 and a value of r_p of 40k, the gain of the final stage is approximately 0.04. It appears possible that the newer balancing systems for recorders for use in high impedance operations will permit a considerable increase in the value of R .

The output impedance of the output stage is a matter of some interest. Assuming the internal impedance of the plate supply to be zero, the output impedance may be analyzed in the following terms:

$$R_{out} = \frac{R_S R_L}{R_S + R_L} \qquad \text{where} \qquad R_S = \frac{2}{\mu + 2}\left[r_p + (\mu+1)R_K\right] \quad \text{assuming}$$

the input grids remain at constant potential. With a feedback connection from each side of R to the corresponding input grids marked by signals e_1 and e_2, via an amplifier of gain -A from each side, the output resistance becomes

$$R_{out} = \frac{R_T R_L'}{R_T + R_L} \qquad \text{where} \qquad R_T = \frac{2\left[r_p + (\mu+1) R_K\right]}{2 + \mu + A\mu}$$

If $\mu = 20$, $r_p = 4000$, $R_k = 100$ and $A = 1000$, then $R_T = 0.6$ ohm

It is important that the filaments of the 6BF7 tubes be supplied with D.C. The supply used for these two tubes and the two 5719's in the preceding stage is a C. J. Applegate model 119 D.C. filament supply. The 5719 stage preceding the output stage is one designed to have large common mode rejection. It is similar to a circuit described by R. McFee (R.S.I. 21, 770, 1950). The first stage is of the same general nature. It will be observed that the output points at a given stage feeding the grids of the following stage are at almost exactly the same potentials as the input points to a given stage. The CK512AX tubes, being filament tubes, require a separate floating filament supply.

The equation for the gain of a given stage as given by McFee is (in his notation) $\frac{e_o}{(e_1 - e_2)} = \frac{R_1}{R_1 + R_2} \frac{\mu R_T}{r_p + R_T}$ where $R_T = \frac{(R_1 + R_2) R_L}{R_1 + R_2 + R_L}$.
This expression is accurate under the following circumstances: it assumes perfectly matched tubes and resistors and in addition assumes that voltages which are exactly equal in magnitude and opposite in phase are fed to the two input grids. Under these circumstances the cathode voltage remains constant. A simple approximation frequently satisfied by practical circuits involves assuming that the currents through resistors R_1 and R_2 are negligible compared with the plate currents. Under these conditions the expressions for the two plate currents are (see Fig. 14)

$$i_{p_1} = \frac{\mu_1 e_1 (r_{p_2} + R_L + R_C + R_K) - \mu_2 e_2 (R_C + R_K) + E_{bb}(r_{p_2} + R_L)}{r_{p_1} r_{p_2} + (r_{p_1} + r_{p_2})(R_C + R_K + R_L) + 2 R_L (R_C + R_K) + R_L^2}$$

$$i_{p_2} = \frac{-\mu_1 e_1 (R_C + R_K) + \mu_2 e_2 (r_{p_1} + R_L + R_C + R_K) + E_{bb}(r_{p_1} + R_L)}{r_{p_1} r_{p_2} + (r_{p_1} + r_{p_2})(R_C + R_K + R_L) + 2 R_L (R_C + R_K) + R_L^2}$$

The sum of the two plate currents is given by the expression

$$i_{p_1} + i_{p_2} = \frac{(\mu_1 e_1 r_{p_2} + \mu_2 e_2 r_{p_1}) + (\mu_1 e_1 + \mu_2 e_2) R_L + E_{bb}(r_{p_1} + r_{p_2} + 2 R_L)}{r_{p_1} r_{p_2} + (r_{p_1} + r_{p_2})(R_C + R_K + R_L) + 2 R_L (R_C + R_K) + R_L^2}$$

hence the voltage across the combination $R_1 + R_2$ is

$$e_{(R_1+R_2)_1} = \frac{-\mu_1 e_1 [(r_{p_2} + R_L)(R_C + R_K) + (R_C + R_K) R_L] - \mu_2 e_2 [r_{p_1} R_K - R_C R_L] + E_{bb}[r_{p_1} r_{p_2} + r_{p_1}(R_C + R_L) + r_{p_2} R_L + 2 R_C R_L]}{r_{p_1} r_{p_2} + (r_{p_1} + r_{p_2})(R_C + R_K + R_L) + 2 R_L (R_C + R_K) + R_L^2}$$

$$e_{(R_1+R_2)_2} = \frac{-\mu_1 e_1 [r_{p_2} R_K - R_C R_L] - \mu_2 e_2 [(r_{p_1} + R_L)(R_C + R_K) + (R_C + R_K) R_L] + E_{bb}[r_{p_1} r_{p_2} + r_{p_2}(R_C + R_L) + r_{p_1} R_C + 2 R_C R_L]}{r_{p_1} r_{p_2} + (r_{p_1} + r_{p_2})(R_C + R_K + R_L) + 2 R_L (R_C + R_K) + R_L^2}$$

If e_1 and e_2 are referenced to the bottom of R_k instead of the top, the effect everywhere is to replace R_c and R_k by $(\mu + 1)R_c$ and $(\mu + 1)R_k$. In particular, the expression for the variational voltage across the T_1 combination of R_1 and R_2 is

$$e_{(R_1+R_2)_1} = \frac{-\mu_1 e_1 \{(r_{p_2}+R_L)(R_K+R_L)+(1+\mu_2)(R_c+R_K)R_L\} - \mu_2 e_2 \{(r_{p_1}+R_L)R_K-(1+\mu_2)(R_c+R_K)\,R_L\}}{(r_{p_1}+R_L)(r_{p_2}+R_L)+(r_{p_1}+r_{p_2}+2R_L)R_K+[(r_{p_1}+R_L)(\mu_2+1)+(r_{p_2}+R_L)(\mu_1+1)]R_c}$$

If the tubes are assumed to be identical, and if we use the expressions

$$e_1 = \tfrac{1}{2}(e_1 - e_2) + \tfrac{1}{2}(e_1 + e_2)$$

$$e_2 = -\tfrac{1}{2}(e_1 - e_2) + \tfrac{1}{2}(e_1 + e_2)$$

then the voltage across R_1 and R_2 is

$$e_{(R_1+R_2)_1} = \frac{-\frac{1}{2}\mu R_L\ (e_1 - e_2)}{r_p + R_L} - \frac{\frac{1}{2}\mu(R_L + 2R_K)(e_1 + e_2)}{r_p + R_L + 2(1+\mu)(R_c + R_K)}$$

The first term represents the gain for a differential input. To calculate the voltage change at the top of R_{2_1} with respect to the reference node, it is necessary to include the voltage change across R_k

$$e_{R_K} = (e_1 + e_2)\frac{\mu R_K}{r_p + R_L + 2(1+\mu)(R_c + R_K)}$$

Then the voltage change at the top of R_{2_1} is

$$e_{R_{2_1}} = -(e_1 - e_2)\frac{\mu}{2}\frac{R_2}{R_1+R_2}\frac{R_L}{r_p + R_L}$$
$$-(e_1+e_2)\frac{\mu}{2}\left[\frac{\frac{R_2}{R_1+R_2}(R_L + 2R_K) - 2R_K}{r_p + R_L + 2(1+\mu)(R_c+R_K)}\right]$$

For zero common mode output,

$$\frac{R_2}{R_1 + R_2}(R_L + 2R_K) = 2R_K$$

$$\text{or}\quad \frac{R_2}{R_1 + R_2} = \frac{2R_K}{R_L + 2R_K}$$

If $R_2 = R_1$, then $R_L = 2R_k$ gives zero common mode gain.

The signal across the other R_2 is

$$e_{R_{2_2}} = -(e_2-e_1)\frac{\mu}{2}\frac{R_2}{R_1+R_2}\frac{R_L}{r_p+R_L} - (e_1+e_2)\frac{\mu}{2}\left[\frac{\frac{R_2}{R_1+R_2}(R_L+2R_K) - 2R_K}{r_p + R_L + 2(1+\mu)(R_c+R_K)}\right]$$

The voltage difference, which is e_0, is

$$e_{o_{12}} = -(e_1-e_2)\,\mu\,\frac{R_2}{R_1+R_2}\;\frac{R_L}{r_p+R_L}$$

If $R_1 = R_2$ and $R_L = r_p$, then the gain for $e_2 = -e_1$ is $\frac{\mu}{2}$

The more general case in which the currents through R_1 and R_2 are not negligible is illustrated in Fig. 15. The expressions for i_{p_1} and i_1 are too complex to be useful in a practical case. Rf $R_L = 2R_k$ and $R_1 = R_2$, the common mode gain is zero, assuming identical tubes. In this case, the gain may be calculated with the expression given by McFee. If the tubes are identical and $e_1 = e_2$, then the common mode gain is given by the expression

$$e_{R_2}\ (\text{common mode}) = \frac{\mu e\left[(R_1+R_2)2R_K - R_2(R_L+2R_K)\right]}{(r_p+2R_L)(R_1+R_2+R_L+2R_K)+(R_1+R_2)(R_L+2R_K)}$$

For the case of $R_1 = R_2$ and $R_L = 2R_k$, the output is $e_o = \frac{\mu R_T}{r_p + R_T}e$ where $e = e_1 = -e_2$ and $R_T = \frac{(R_1+R_2)R_L}{R_1+R_2+R_L}$

In many cases $r_p \sim R \sim R_1$. For such a situation, the gain is $\frac{\mu}{3}$. In case an electrometer input stage is of this variety, there will ordinarily be a voltage loss since the μ of most electrometer tubes is less than 2. The second stage then assumes importance so far as the problem of minimizing drift is concerned.

It will be observed that this amplifier uses 100% negative feed-back. In the ideal case for infinite loop gain, the gain with feed-back would be identically one. The measured gain is 0.783. Using the usual expression for gain in a negative feed-back amplifier with a value for β of 1, $G = \frac{-A}{1+A}$ The apparent loop gain without feed-back is $A = 3.61$. Since the gain of the final stage is 0.04 the gain product of the first two stages is approximately 90. It is apparent that a considerable improvement in operation could be effected if the gain product for the first two stages could be increased appreciably. Reducing the load resistance at the amplifier output would also improve the situation considerably.

It is possible to evaluate the output impedance of the entire amplifier with the aid of a circuit as indicated in Figure 16. With a constant input voltage to the amplifier the load across the output is varied and the corresponding output voltage is measured. The expression for the output voltage is as follows:

$$E_o = E_A \frac{R}{R + R_{in}}$$

Rearranging this equation gives the following form:

$$R = E_A \frac{R}{E_o} - R_{in}$$

It will be observed that if R is plotted as a function of $\frac{R}{E_o}$, the curve so generated should be a straight line with a slope equal to the input voltage and an intercept determined by the internal resistance of the amplifier. The experimental value for internal impedance is 15.3 ohms. The same set of data permits determination of the overall gain of the amplifier previously quoted as 0.783.

As mentioned previously, a primary function of the amplifier is to act as an impedance transformer. The input impedance is variable in eleven steps from about 5000 ohms to 1600 megohms. The output impedance remains constant. Actually it is a current amplifier with constant voltage sensitivity but with a current sensitivity depending upon the choice of input resistor.

An important feature is the amplifier linearity. This was determined by applying successive known voltage steps and measuring on the recorder the corresponding deflections produced. A plot of the differences between the measured deflections and corresponding deflections for a perfectly linear amplifier indicates that the amplifier is linear to within 0.1% over the measured range of 0 - 10 mv.

In addition to the above features it is desirable for the amplifier to have very small input current. The CK512AX tube is very good in this respect. It was found that the grid current is strongly dependent upon the screen voltage. The screen supply consists of a two decade potentiometer connected with associated resistors across the +260 volt regulated supply. The two decades permit varying the screen voltage from 13.85 volts to 15.10 volts in 100 steps. After adequate warm-up time the grid current is evaluated by switching the input resistor from a low value to a large value and observing the change in output voltage. Adjusting the screen voltage permits reducing the grid current to such a value that switching the input resistance from 0 to 1600 megohms produces a change in output voltage by less than 2% of full scale. This corresponds to a grid current of approximately 10^{-13} amp.

The stability problem in a D.C. amplifier frequently is a vexing one. This amplifier may be used within two minutes after turning on the power supply voltages and after a ten minute warm-up time, will stay within 5% of full scale on the zero to 10 millivolt recorder indefinitely, at constant ambient temperature. The random drift is no more than 1% of full scale and the average drift per hour after warm-up of one hour is approximately 1% of full scale. This corresponds to an output drift voltage of 0.1 millivolt. It is of some interest in this connection that the output drift is not primarily a function of grid current. The evidence for this is that the drift in the output is fairly independent of the input resistance. The drift figures quoted above refer to an input resistance of 1600 megohms. To achieve this degree of stability requires great care in the regulation of associated voltage supplies.

It will be observed that the D.C. amplifier altogether requires five supplies. One is the D.C. heater supply for the 5719 and 6BF7 tubes. The CK512AX tubes require a separate floating filament supply. The plate voltage for the amplifier is a floating supply of 140 volts, while the screen supply has been described above. In addition there is a regulated zero control supply of variable voltage and reversible polarity. The zero control supply and the CK512AX filament supply have several features in common and may be described together. Each uses a selenium rectifier and a low voltage transformer. Stabilization is effected by floating a dry cell at such a location that the supply voltage difference at those points equals the dry cell voltage. New dry cells have internal resistances of no more than 0.1 ohm at 60 cycles and therefore act very well as filters. To avoid drawing current from the stabilizing batteries when power is not applied to the circuit, relays open the dry cell connections when power is off. This method of stabilization has proved very effective. The stability figure quoted above was obtained with a constant voltage transformer between the line and the input transformer. There is an appreciable drift produced by changes in the heater voltage for the 6BF7 and 5719 tubes.

The floating plate supply for the D.C. amplifier uses battery standards and has a circuit diagram as indicated in Figure 17. It will be observed that this power supply uses battery standards throughout. The regulation factor of this power supply may be described in terms of the relationship obtained previously

$$\frac{e_{R'}}{e_R} = \frac{1}{\frac{r_p}{Z_i} + 1 + \mu(1 + \alpha G)}$$

Using measured values for μ and r_p for each tube the gain from the input grid of the first 6SL7 to the control grid of the 6SN7 series control tubes is approximately 50,000. The value for α, the rat io of sample voltage to output voltage, is 0.35. This gives a calculated value of ripple voltage without feed-back to ripple voltage with feed-back of 325,000. Since the load current itself is small, the ripple voltage at the output of the power supply filter is fairly small. The measured value with normal load current was 0.2 volts. Consequently if no other voltage source arises, the ripple voltage at the output should in theory be approximately 10 microvolts. The measured amplitude was less than 2 millivolts, with some difficulty in obtaining the measures because of pickup in the oscilloscope leads. There is no real advantage in increasing the gain of the regulating amplifier unless the first tubes in the regulating amplifier are supplied with D.C. for their heaters. In addition, problems with stray pickup become very acute.

It was found that with a large capacitance across the output there was still an appreciable A.C. ripple voltage with respect to ground. This was reduced to approximately 3 millivolts by adding two more capacitors across the output in series and connecting the series junction to ground through a capacitor. This point may not be connected directly to ground since the power supply used must float with respect to ground and have a fairly small time constant for changing its potential relative to ground.

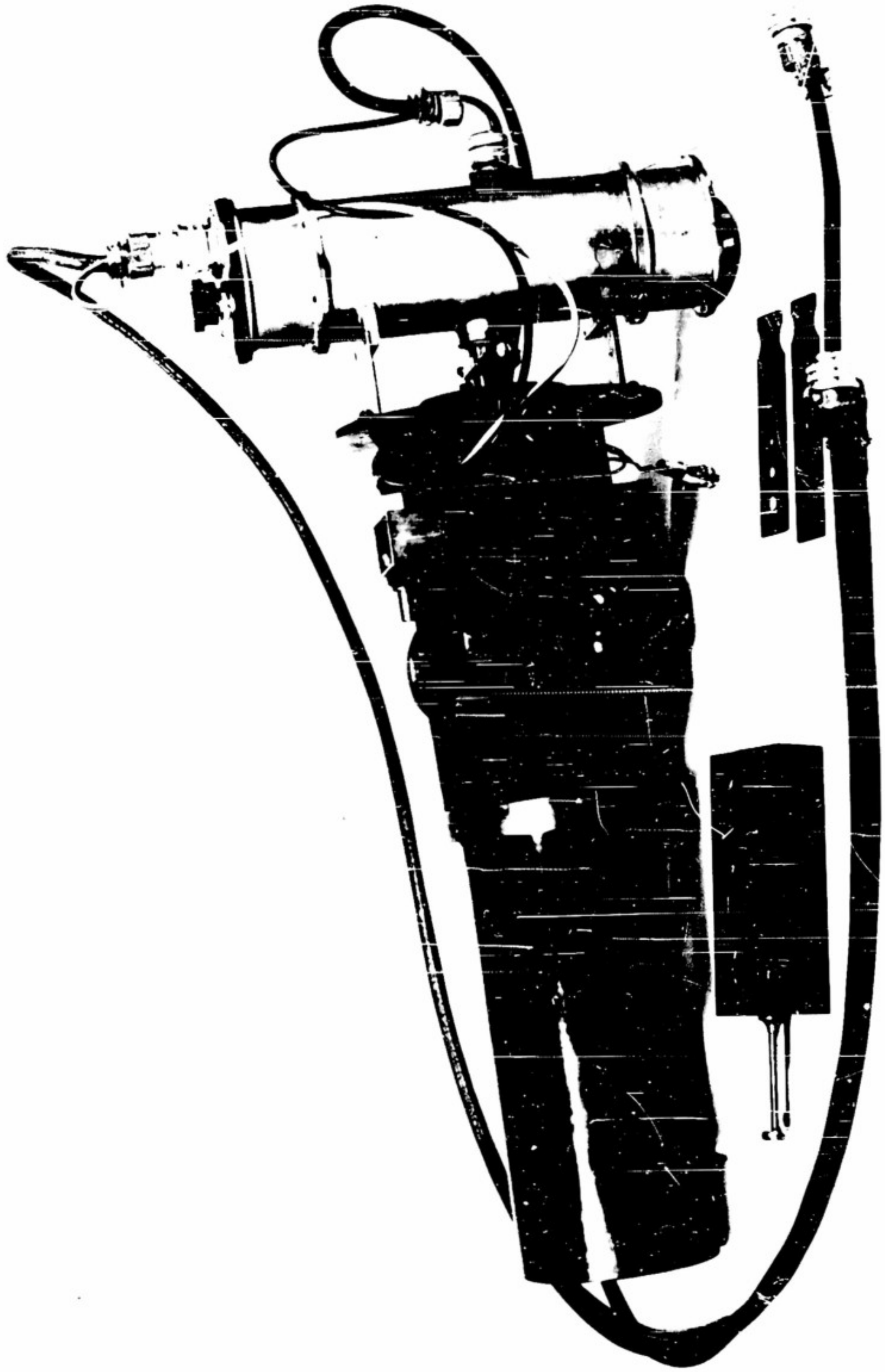
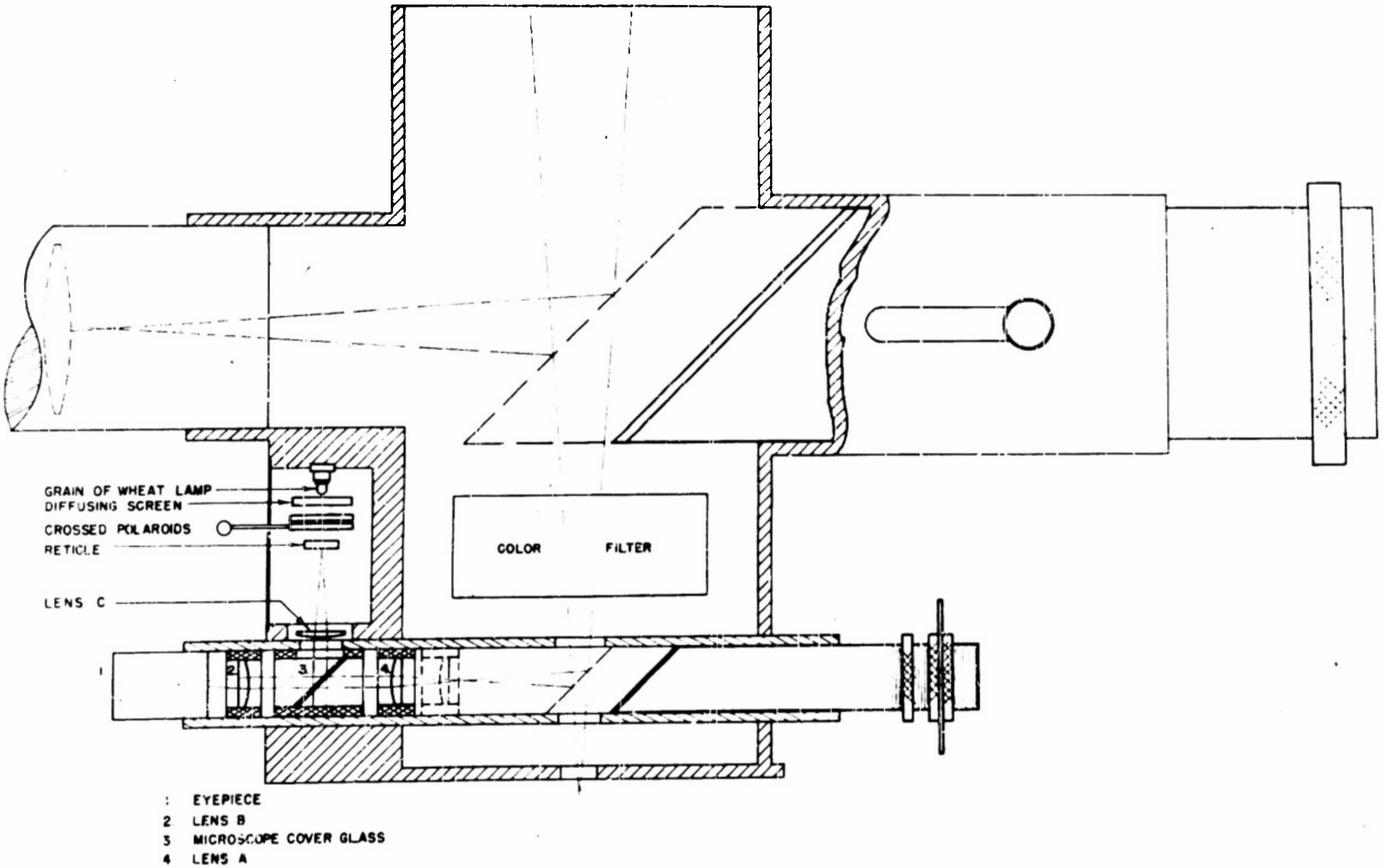


FIG. 2



GRAIN OF WHEAT LAMP
DIFFUSING SCREEN
CROSSED POLAROIDS
RETICLE
LENS C
COLOR FILTER
1 EYEPIECE
2 LENS B
3 MICROSCOPE COVER GLASS
4 LENS A

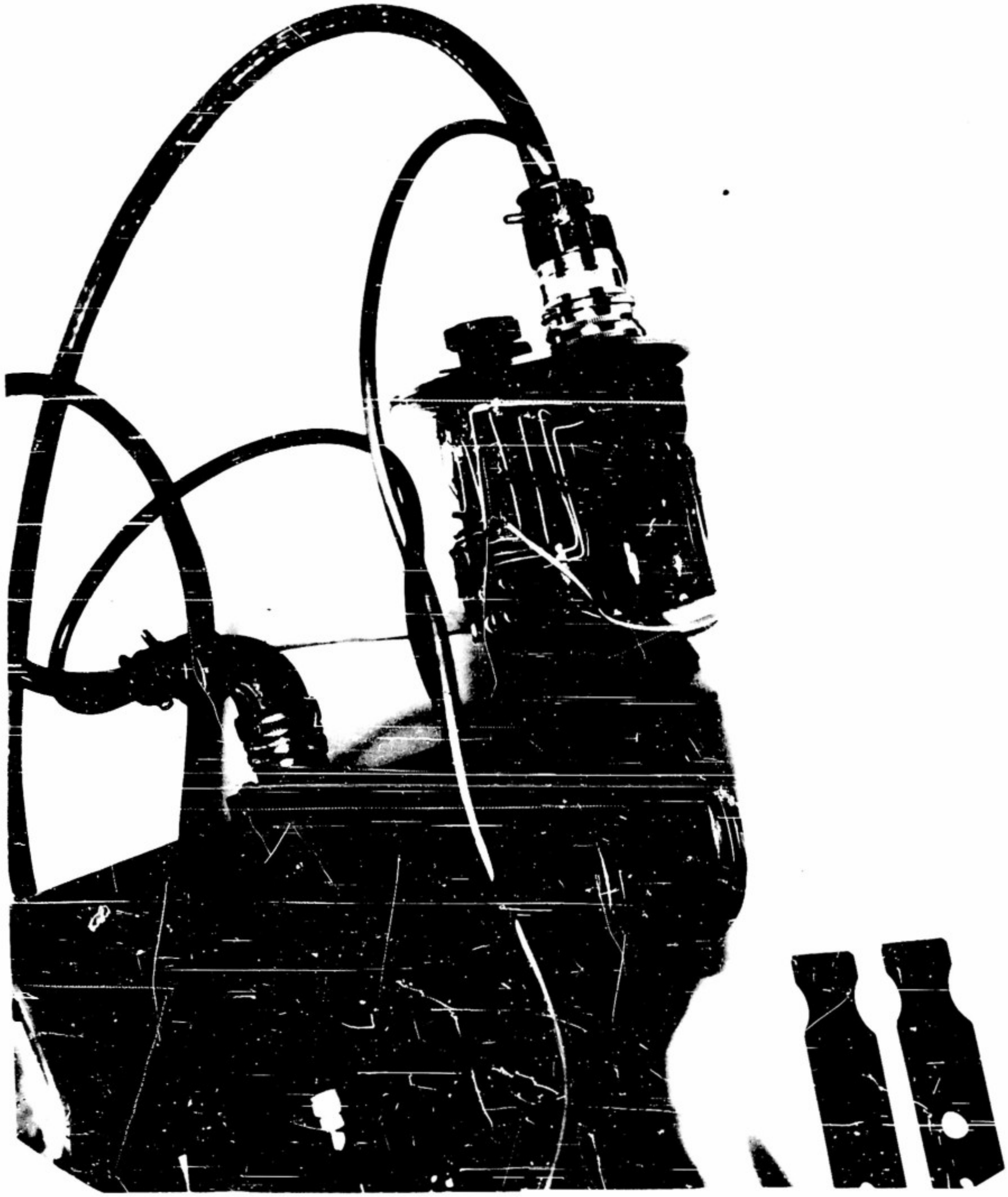


FIG. 5

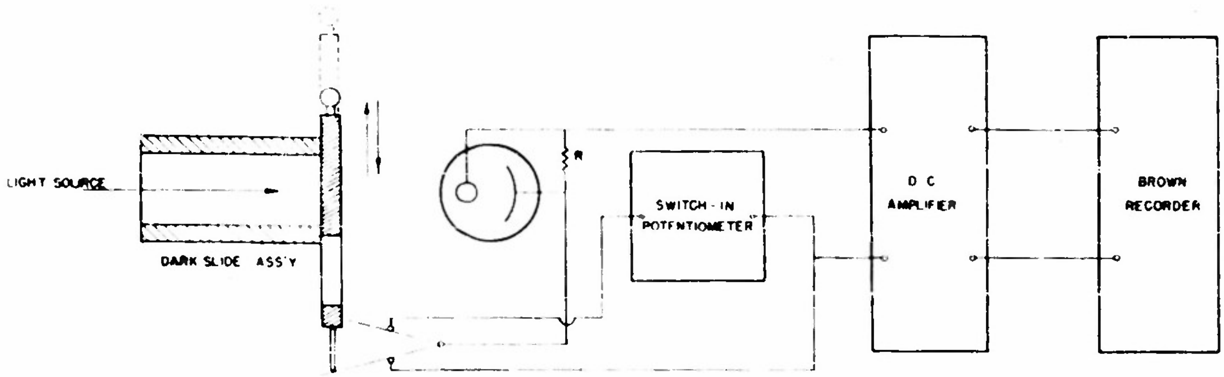


FIG. 7

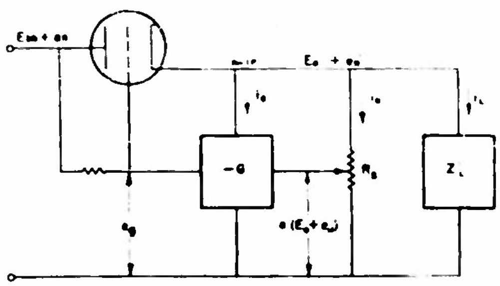
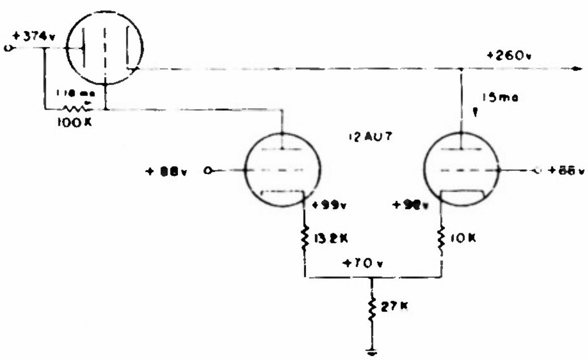


FIG. 9



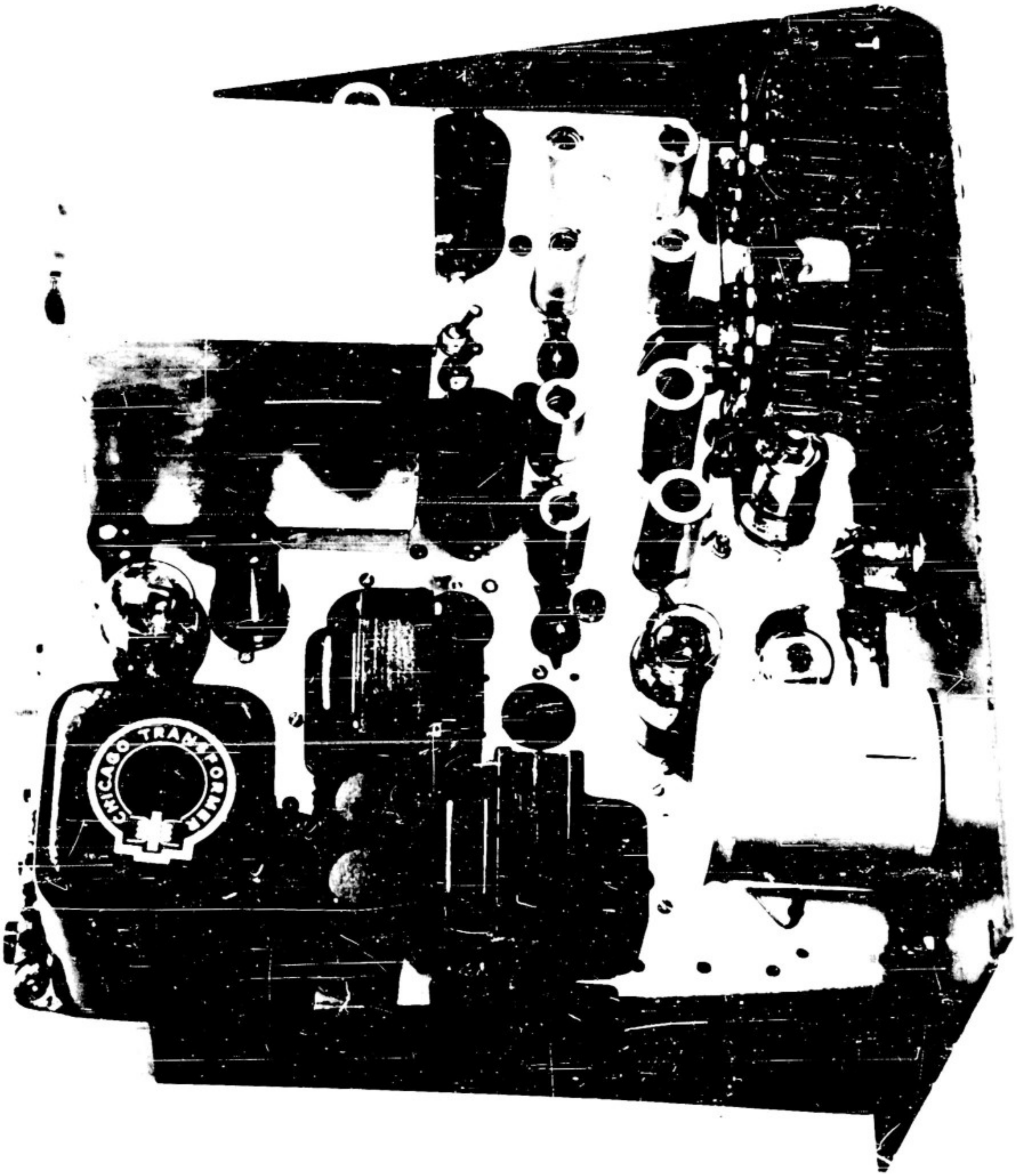
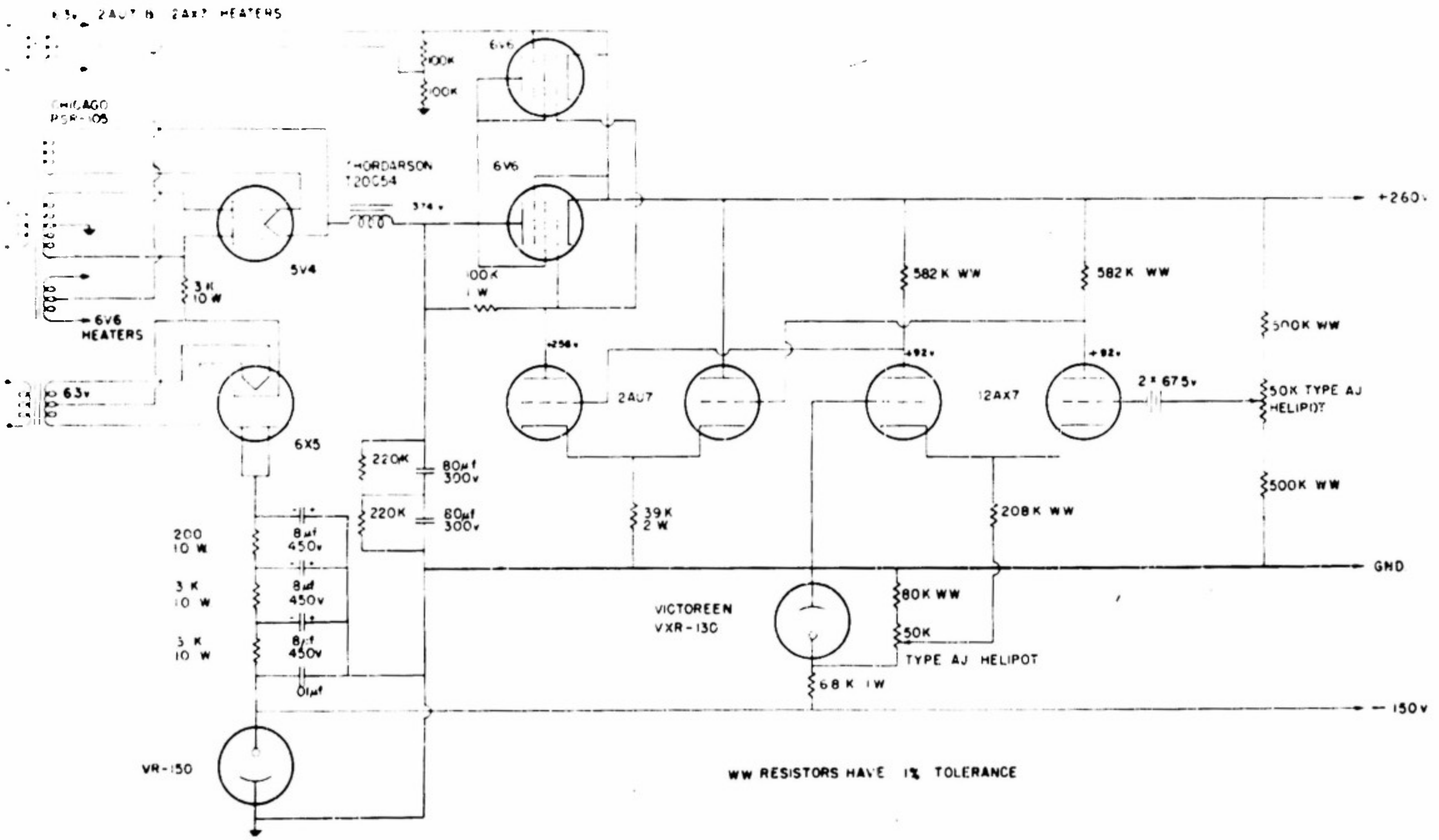

CHICAGO TRANSFORMER

FIG. 8, +260v. REGULATED SUPPLY



WW RESISTORS HAVE 1% TOLERANCE

FIG. 10, SWITCH-IN POTENTIOMETER

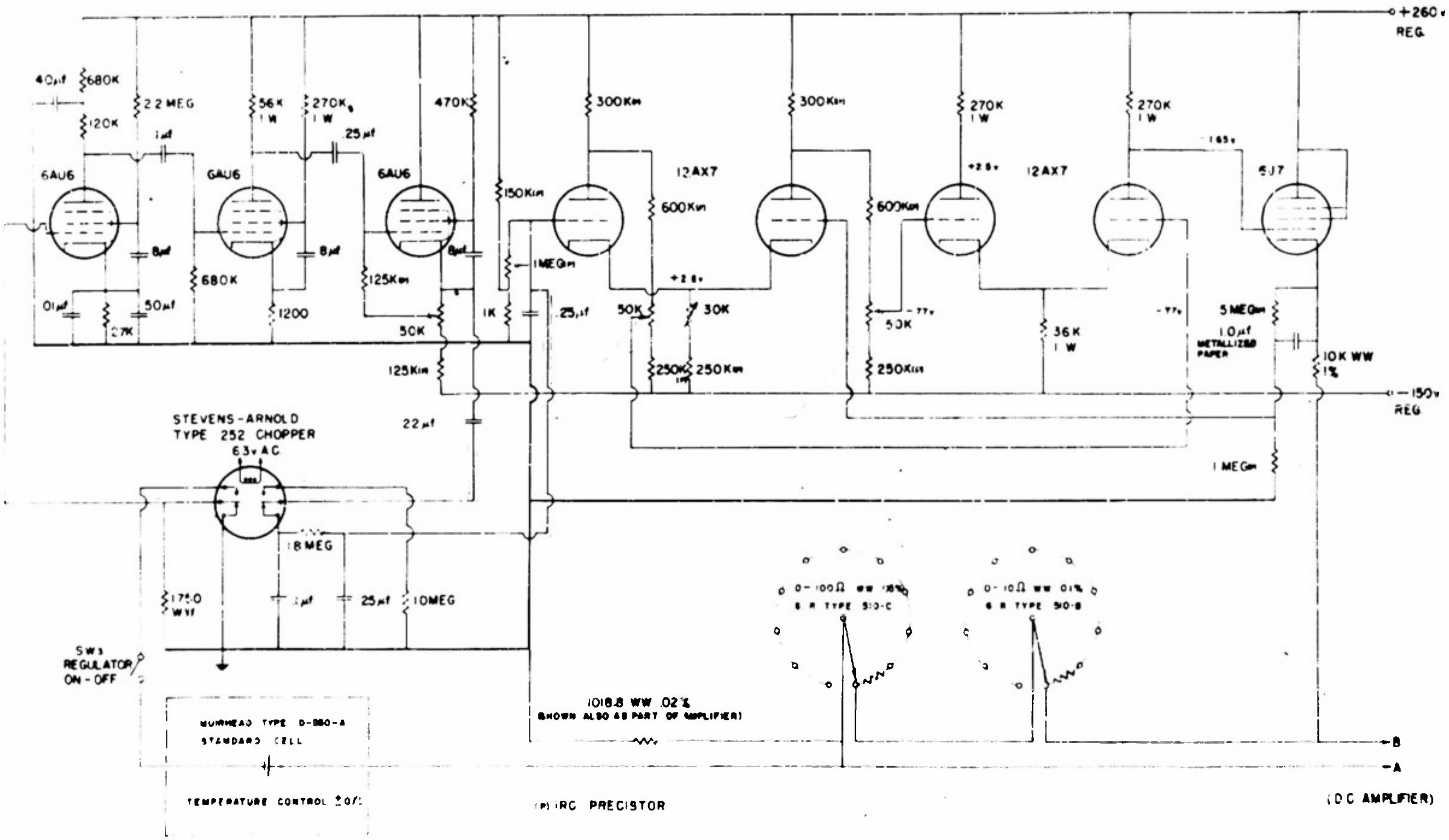


FIG. 11, PHOTOMULTIPLIER SUPPLY

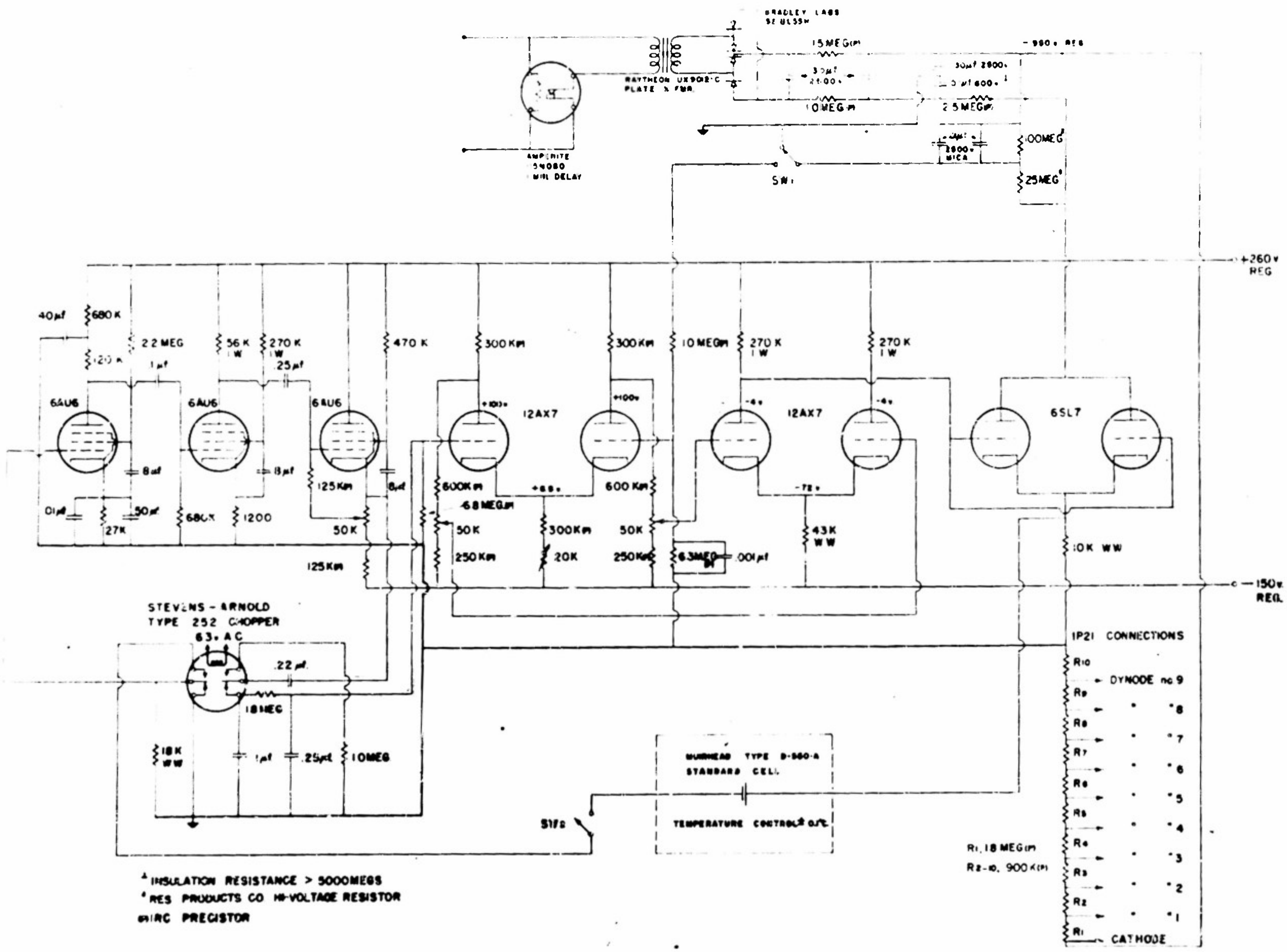


FIG 12, D.C. AMPLIFIER

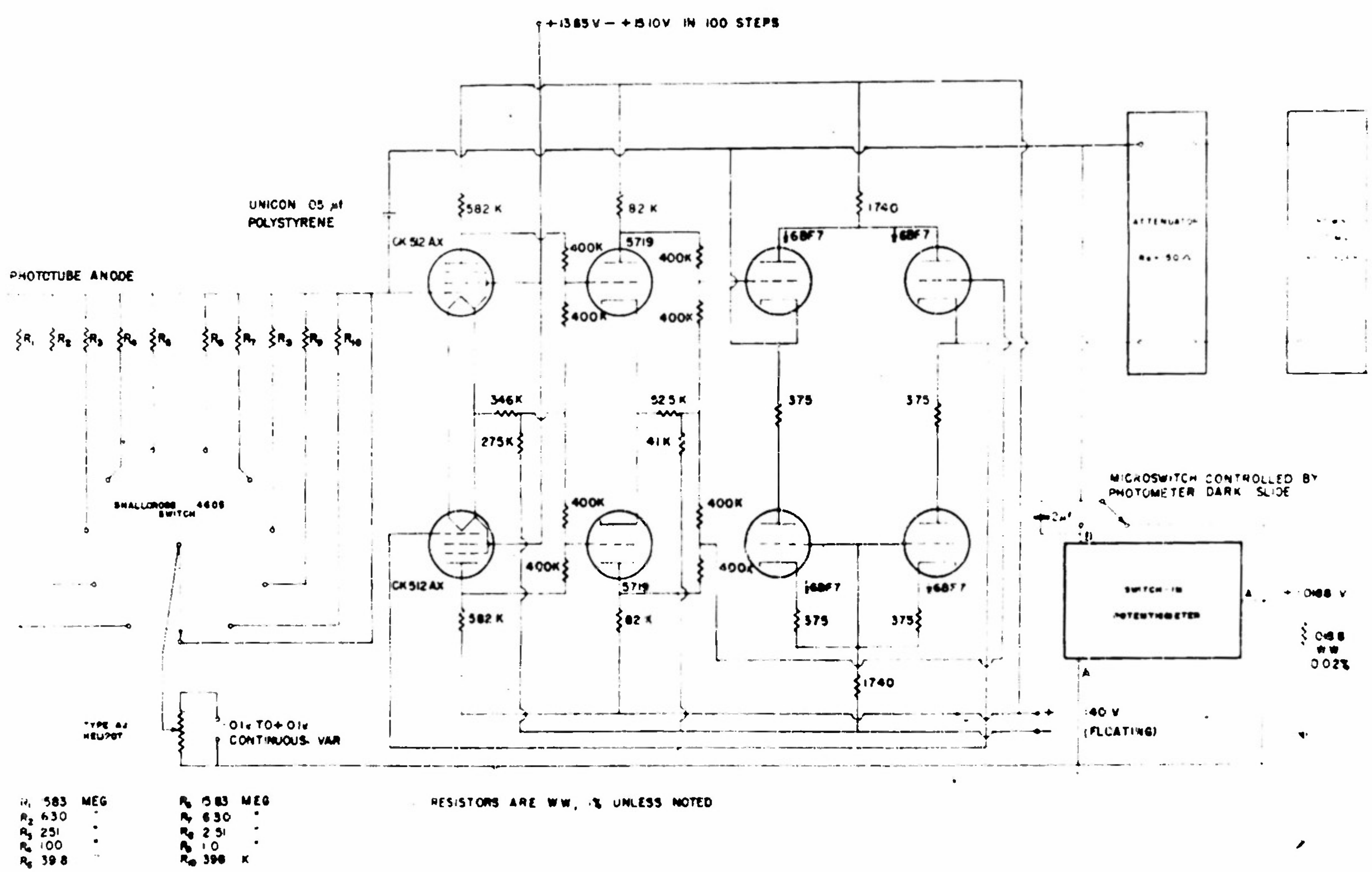


FIG. 13

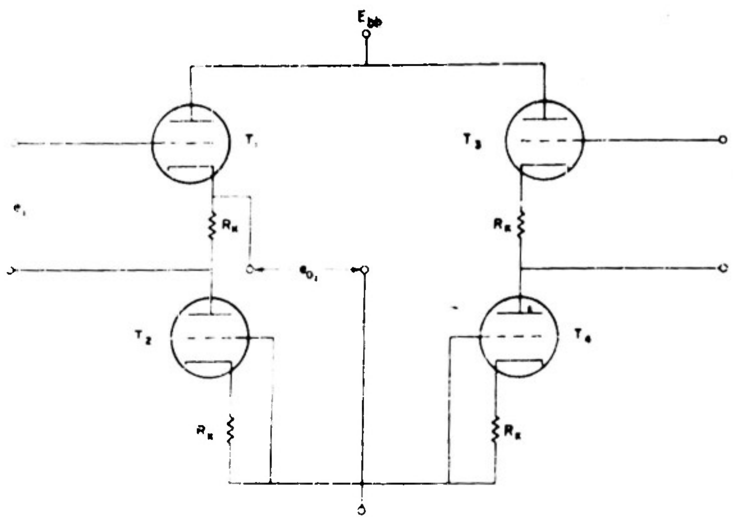


FIG. 14

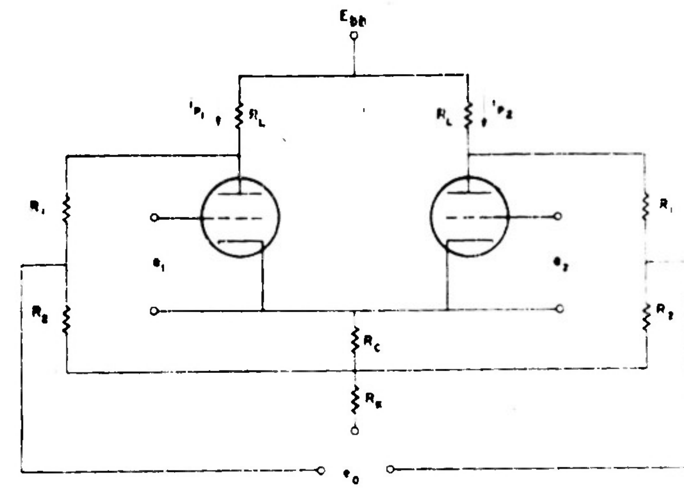


FIG. 15

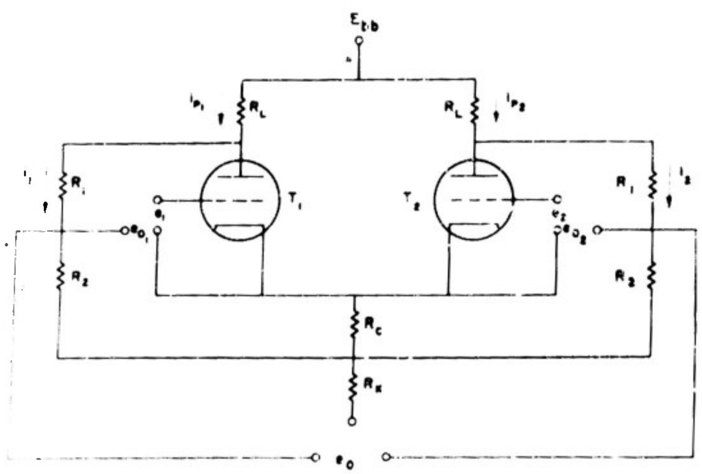


FIG. 16

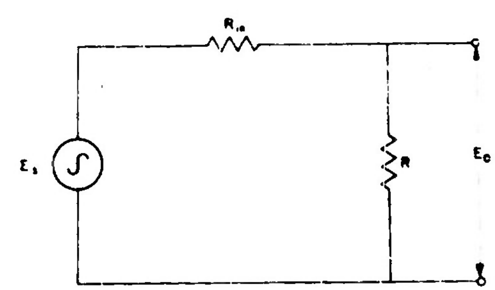


FIG. 13a

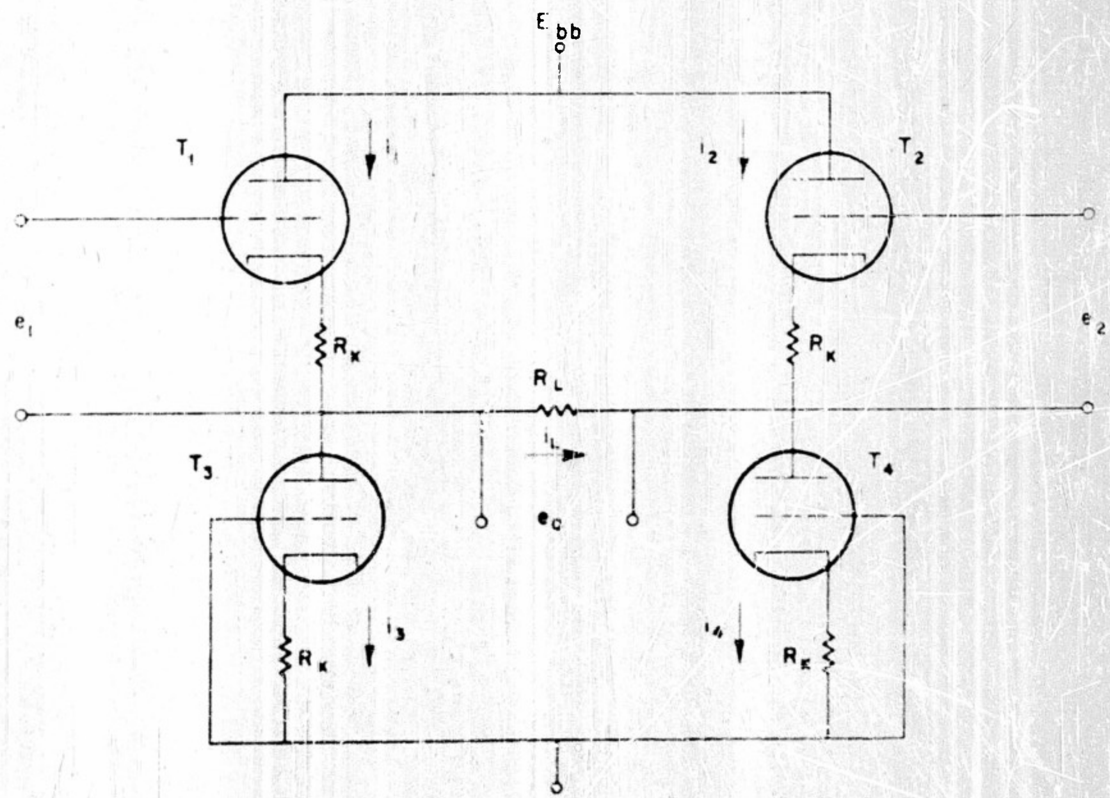
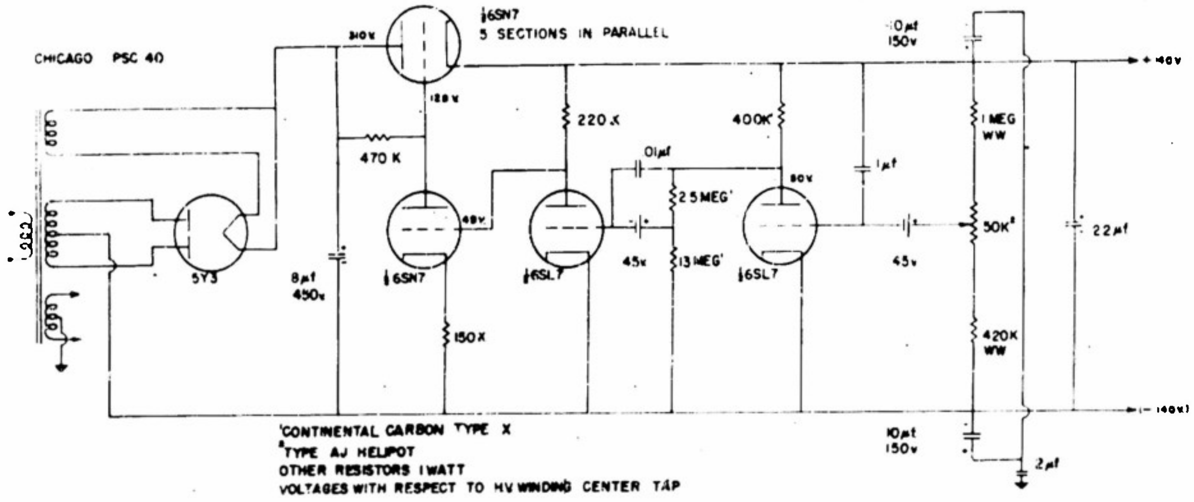
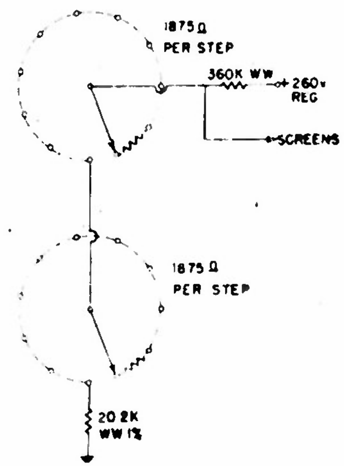


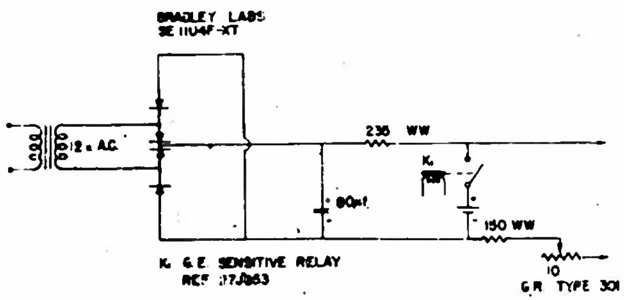
FIG. 17, AMPLIFIER SUPPLIES



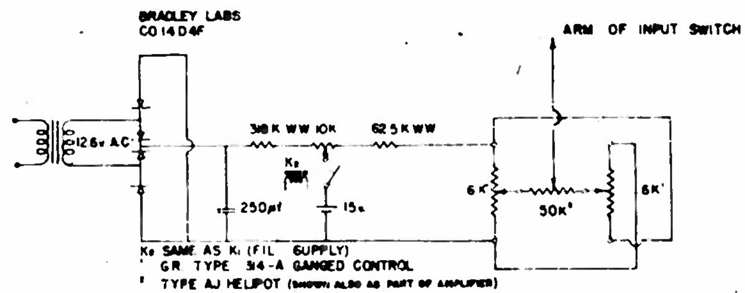
AMPLIFIER B SUPPLY



CK 512 AX SCREEN SUPPLY



CK 512 AX FILAMENT SUPPLY



ZERO CONTROL SUPPLY